3D Laser Printing

Direct Conversion of Information to Matter

Martin Wegener

Karlsruhe Institute of Technology (KIT), Germany

MSE Day, Hereon (Geesthacht), November 14, 2023

- From Bits & Voxels to Matter

- Recent Examples

  ... Ultrafast Polymer Laser Microprinting
  ... Optical In-Situ Diagnostics

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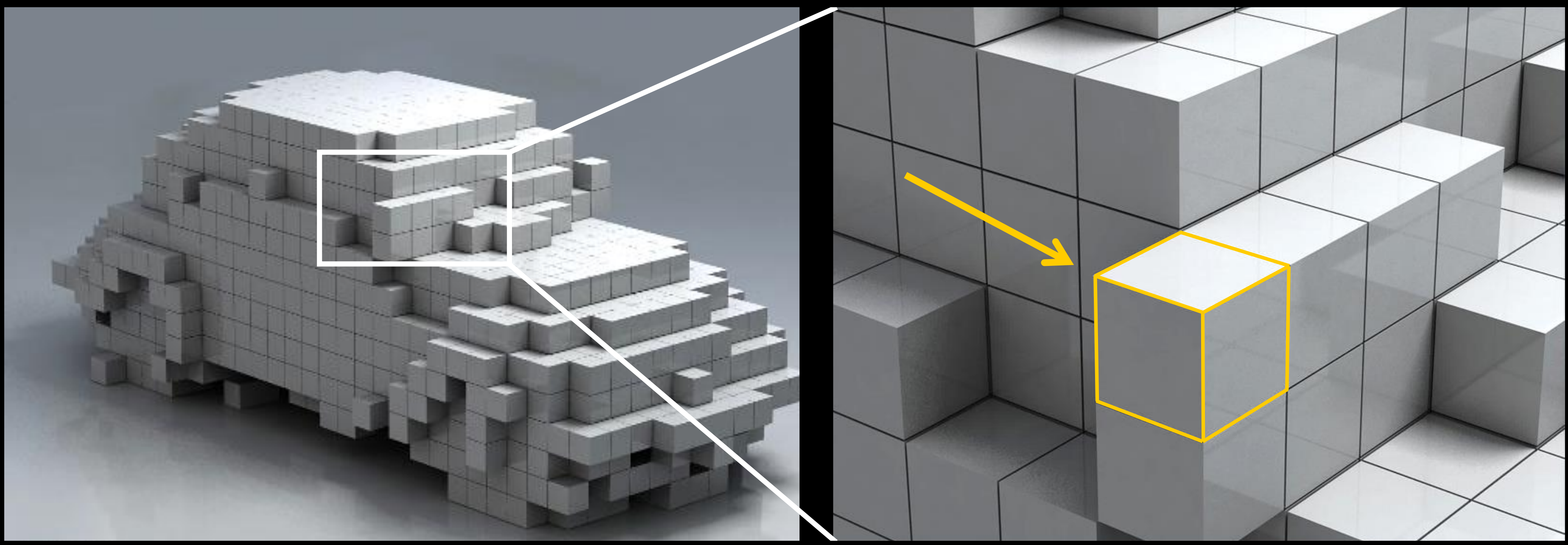
Voxelation of an Object

3D Voxel – the Analogue of a 2D Pixel



Bildquelle: www.bilderzucht.de/blog

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Martin Wegener

Mechanical – Optical

image source: www.dabonline.de/2020/01/03/beton-aus-der-duese-3d-drucker/

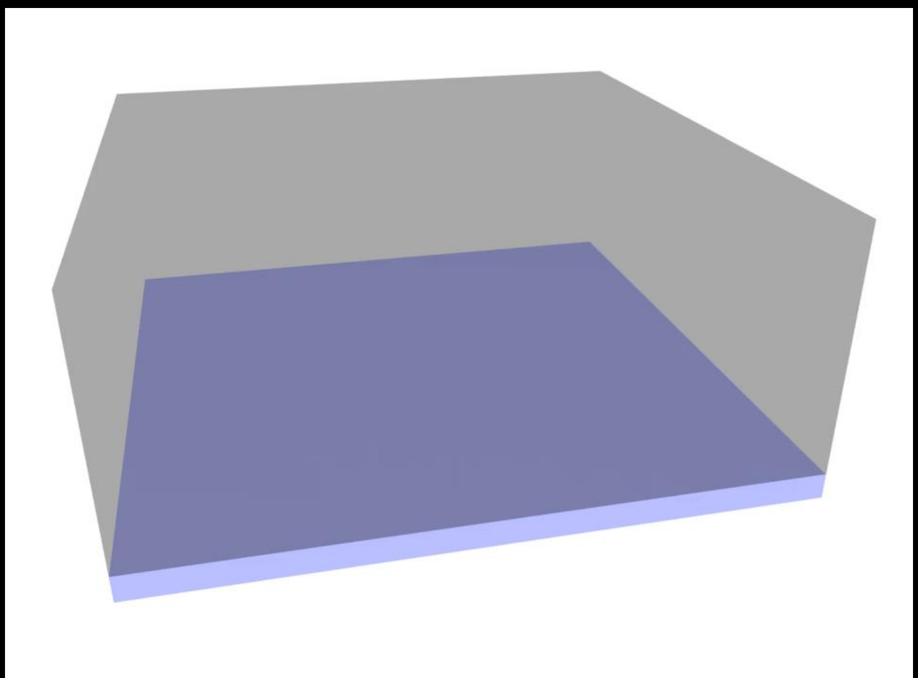

image source: www.3dmattermadetoorder.kit.edu/laser_nanoprinting.php

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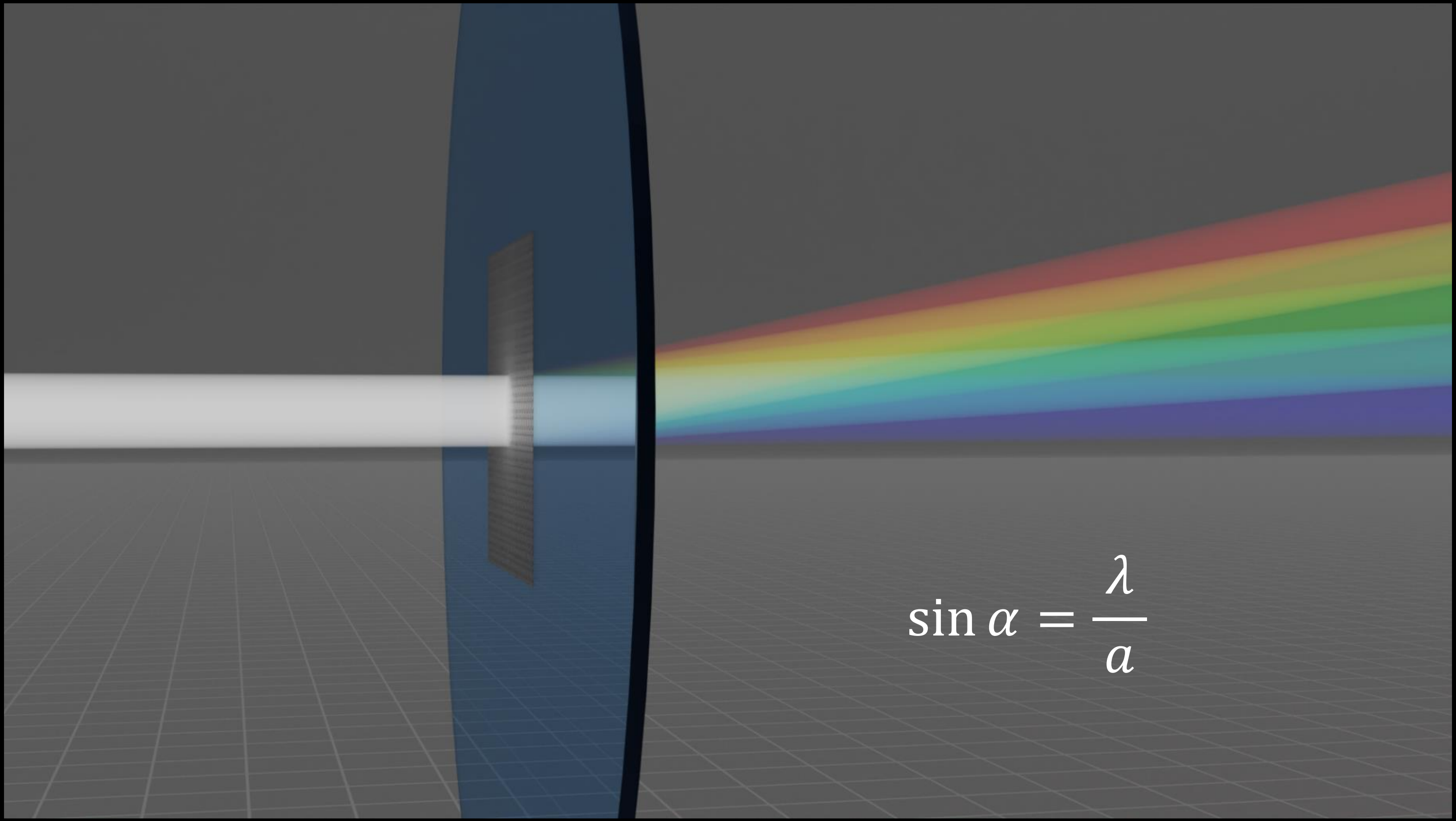
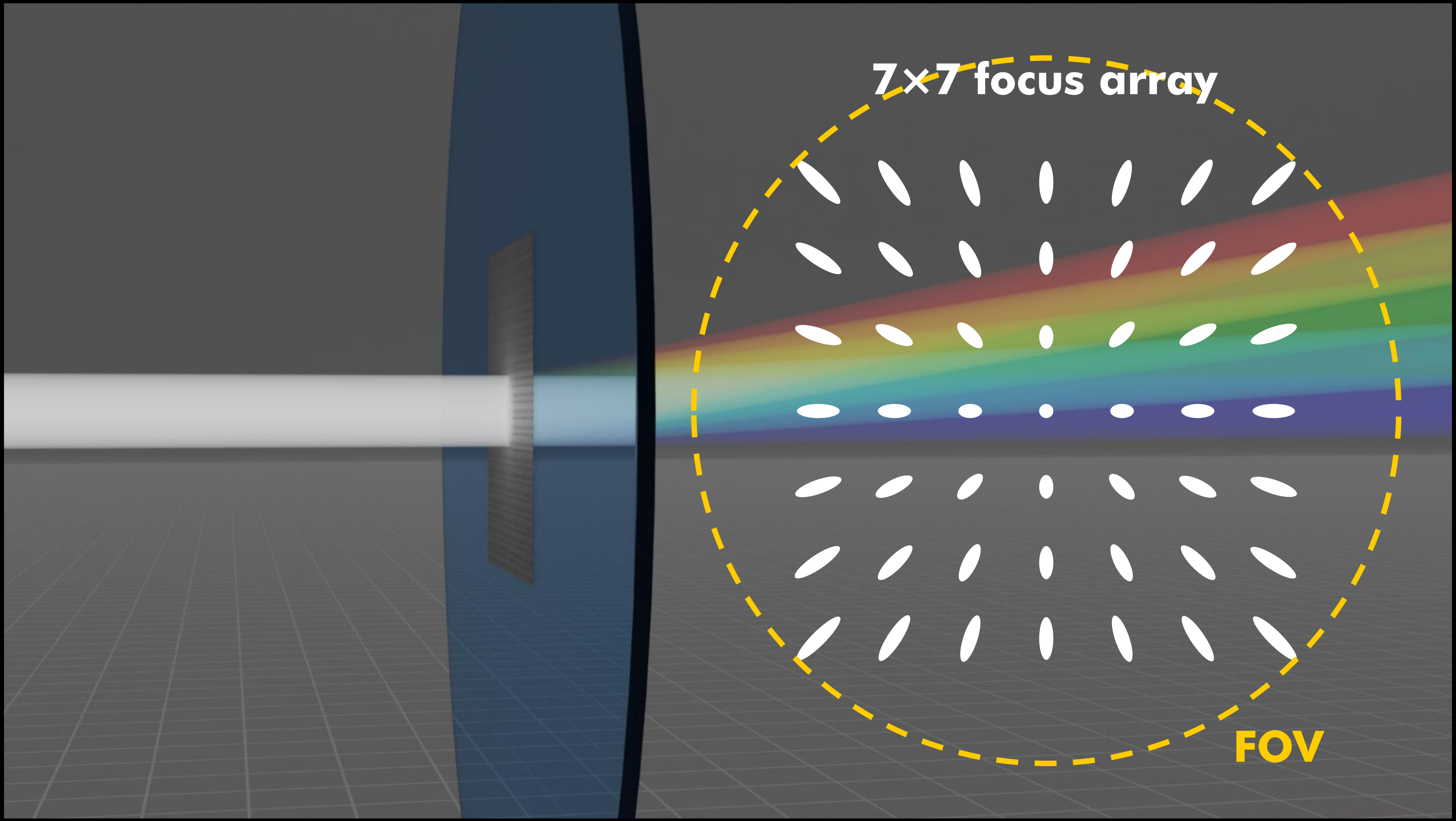
Diffractive Optical Element (DOE)



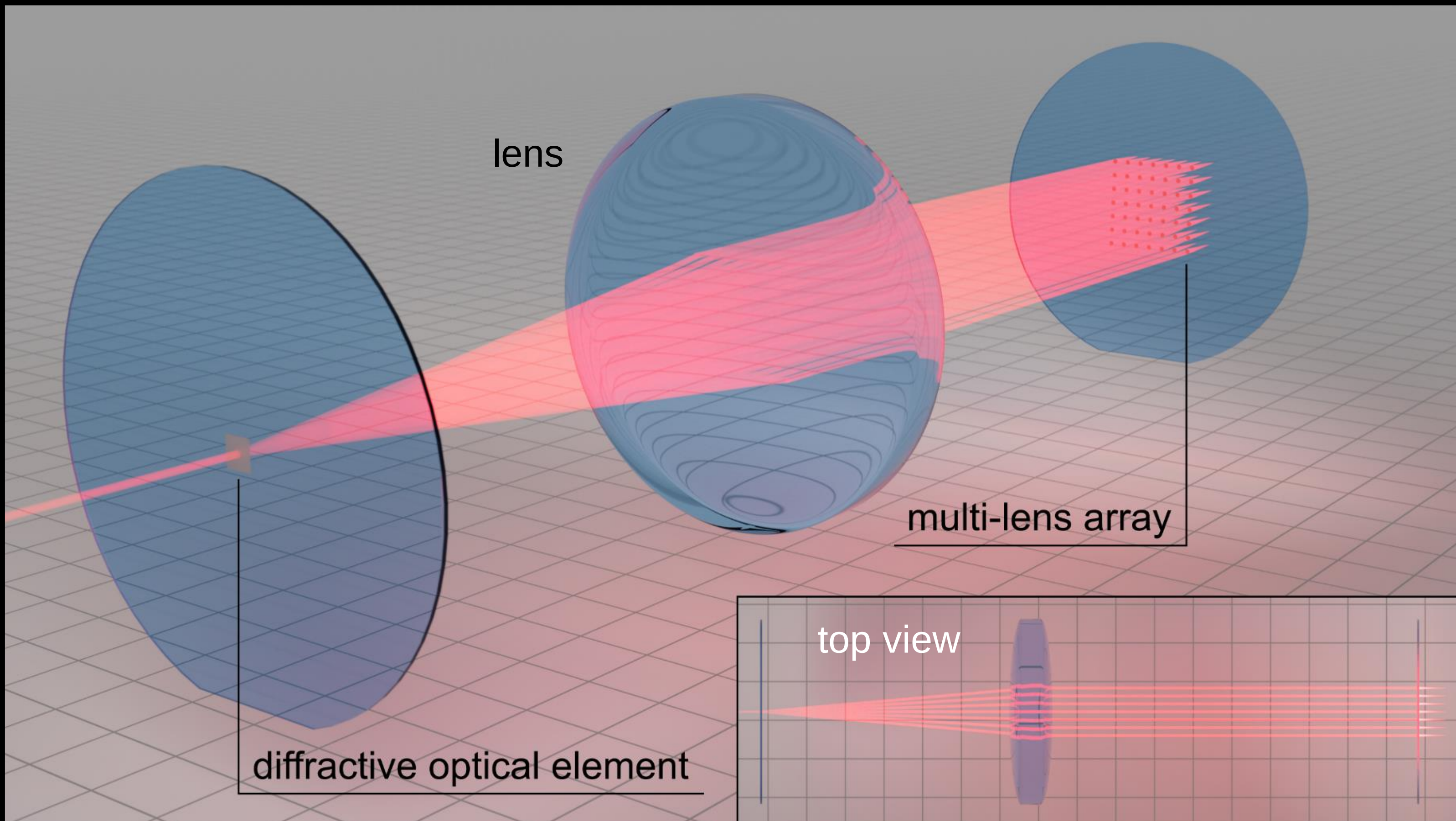
scheme, not to scale

Diffractive Optical Element (DOE)



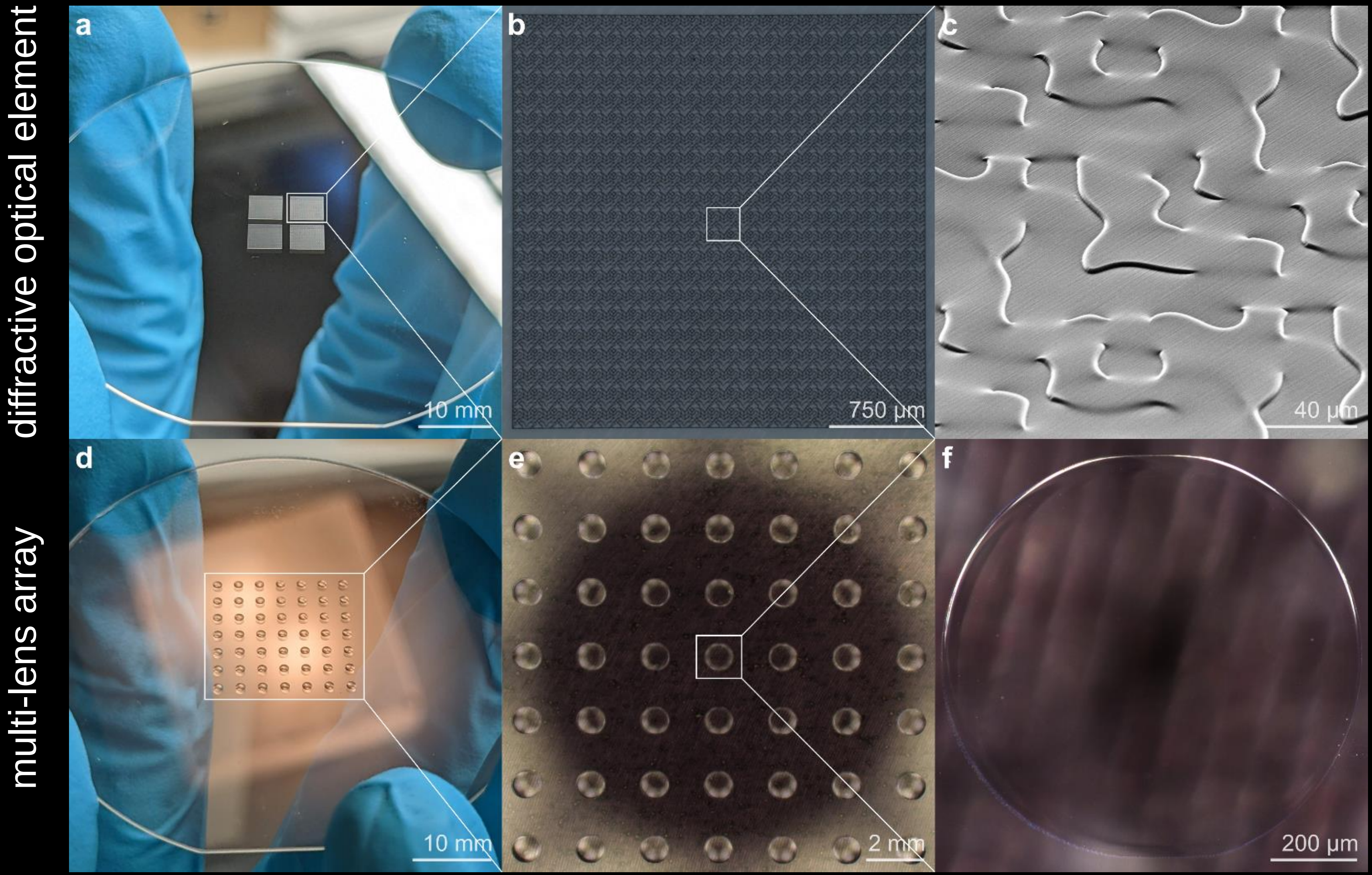
can be compensated: V. Hahn *et al.*, Adv. Funct. Mater. 30, 1907795 (2020)

DOE and Multi-Lens Array (MLA)



P. Kiefer *et al.*, submitted (2023)

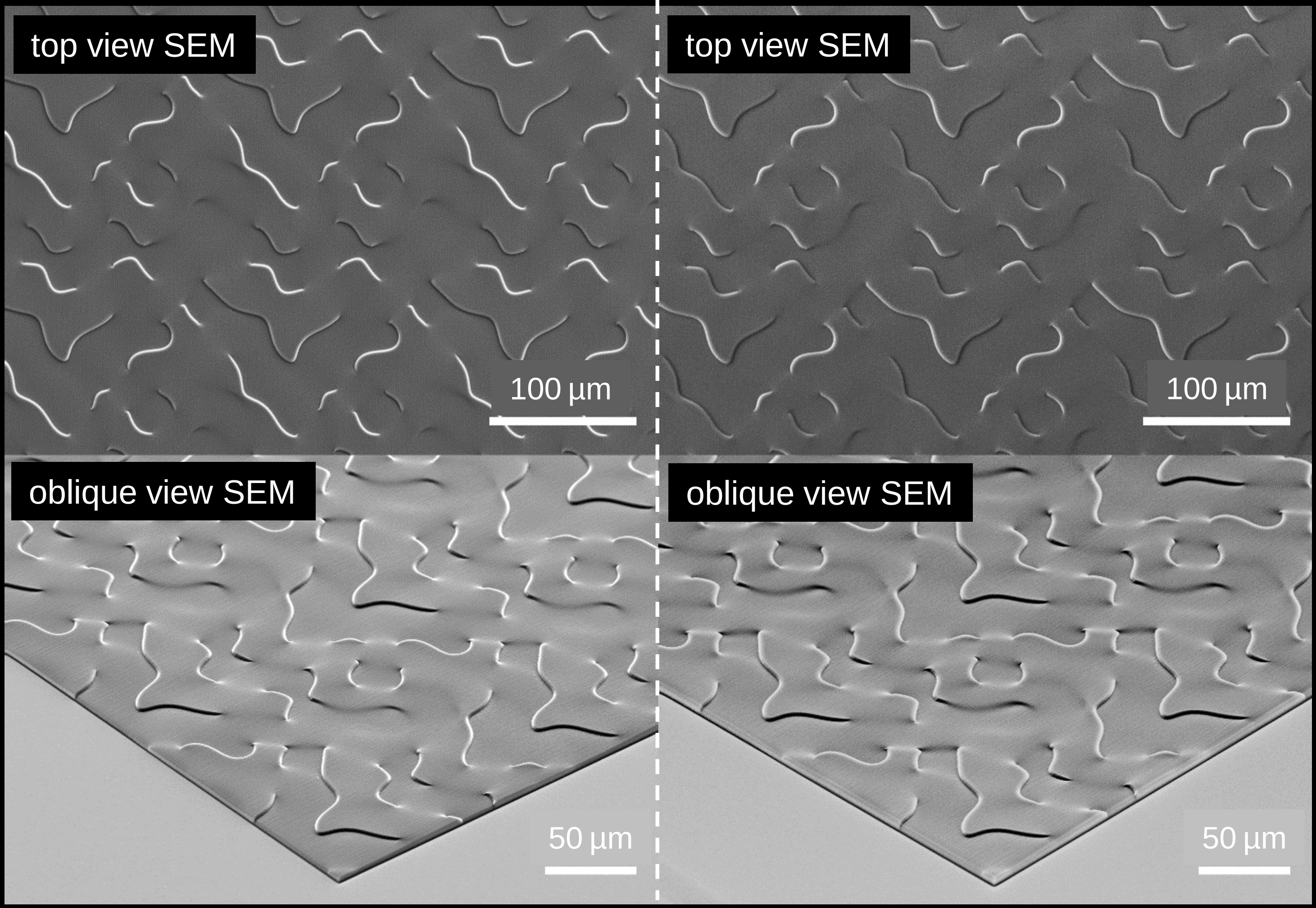
Laser-Printed DOE & MLA



printed using Nanoscribe Quantum X

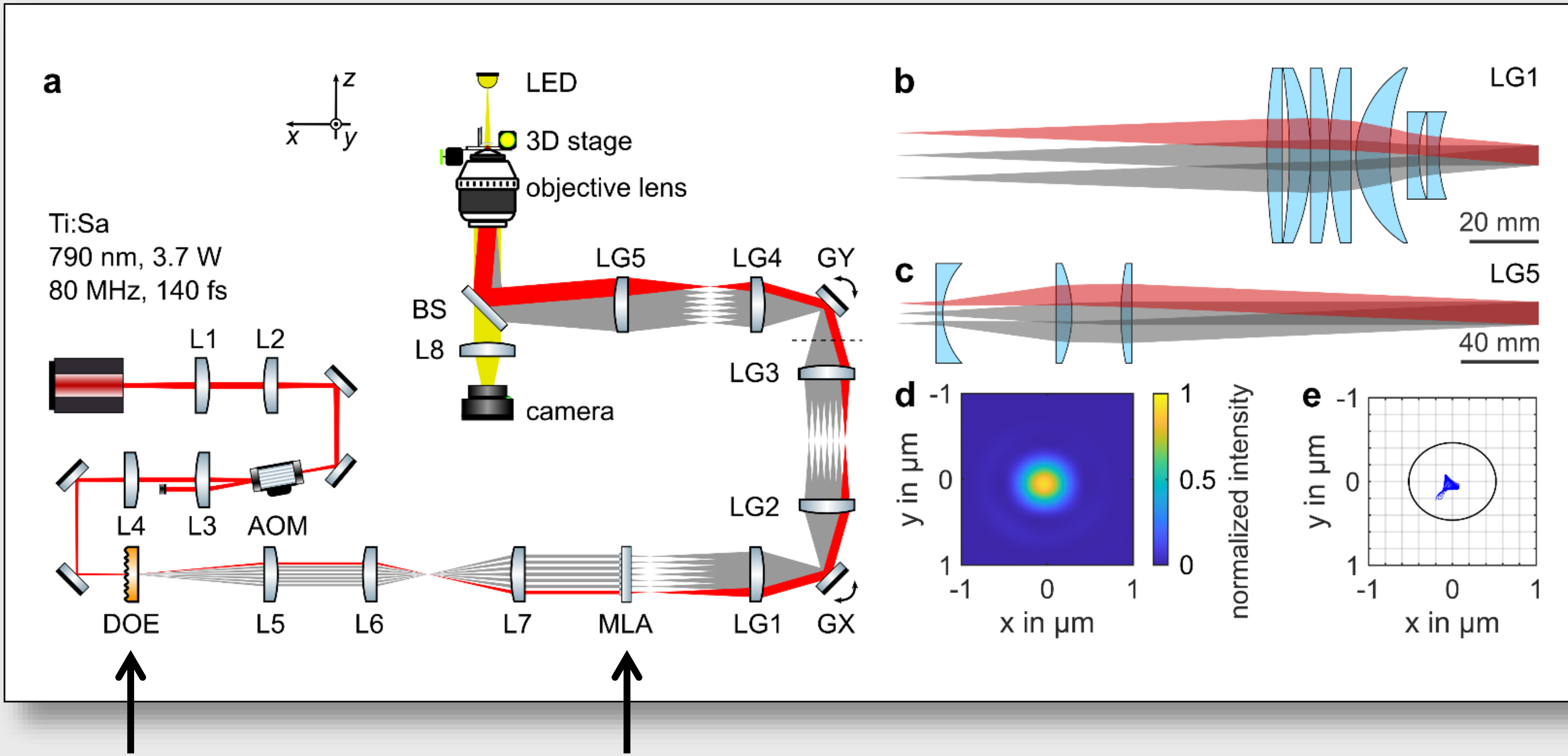
Iterative Precompensation

before | **after**



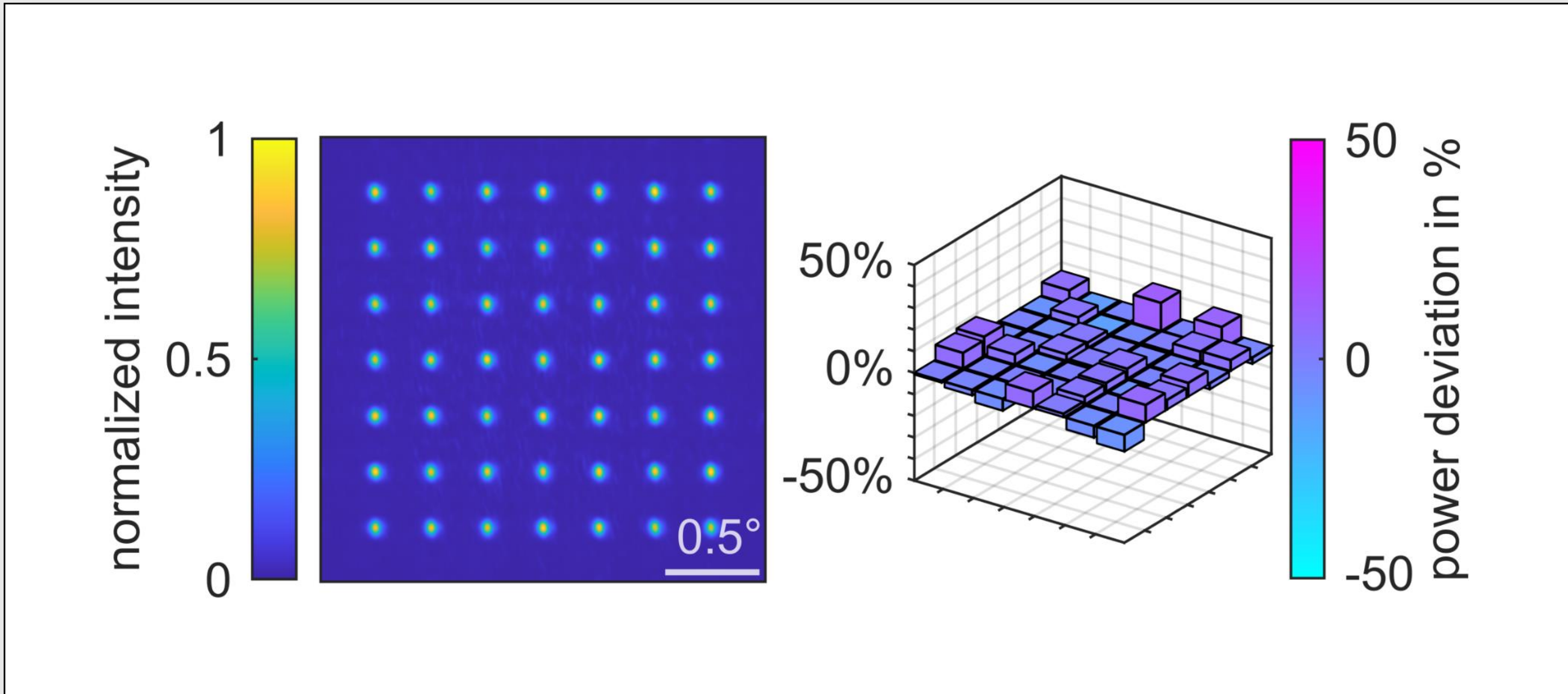
differences not visible by SEM; J. Weinacker *et al.*, submitted (2023)

Multi-Focus Multi-Photon 3D Printer



P. Kiefer *et al.*, submitted (2023)

7×7=49 Laser Foci

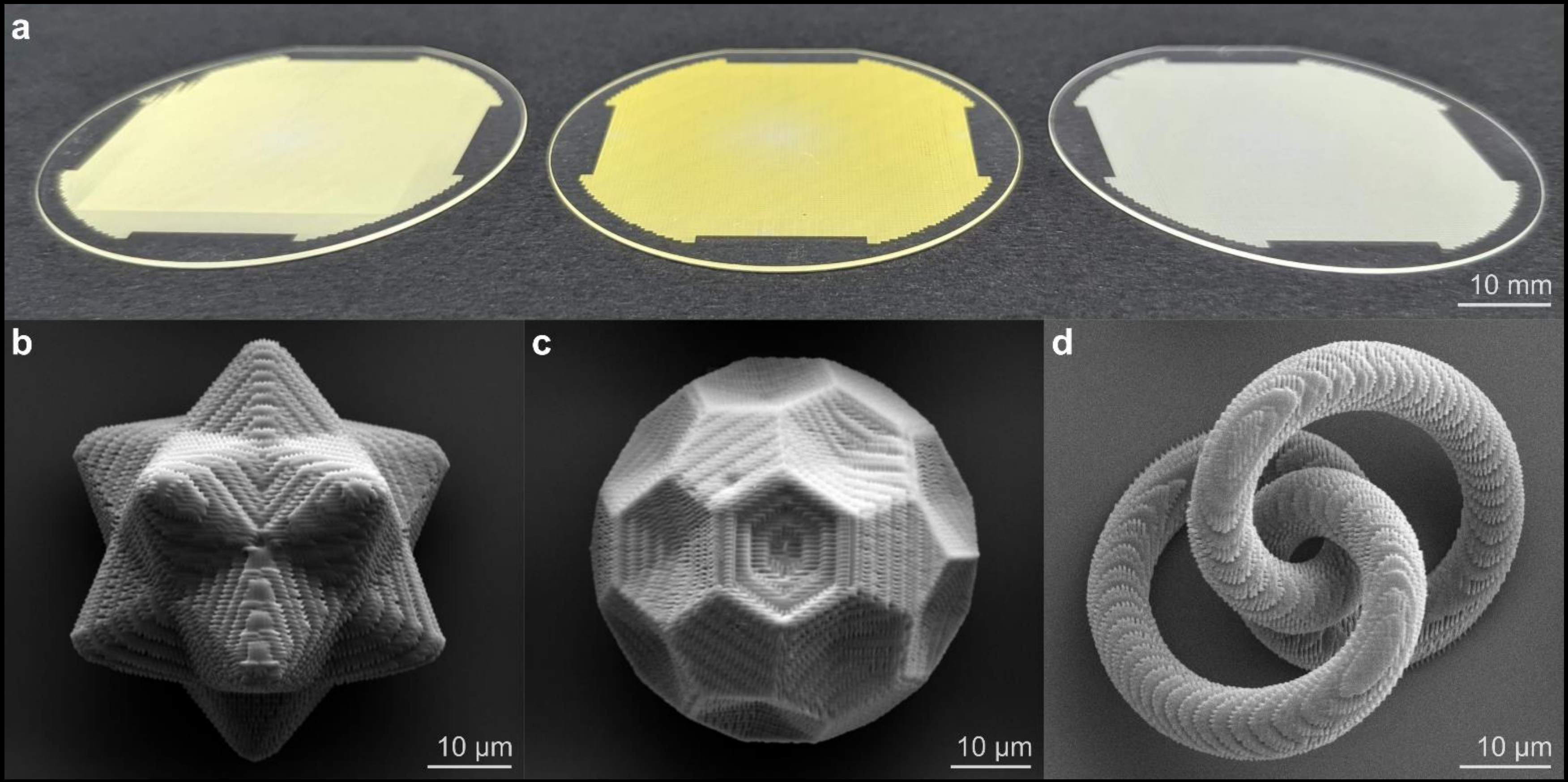


about 1/3 of the fs-laser power enters the entrance pupil of the microscope lens

Example I

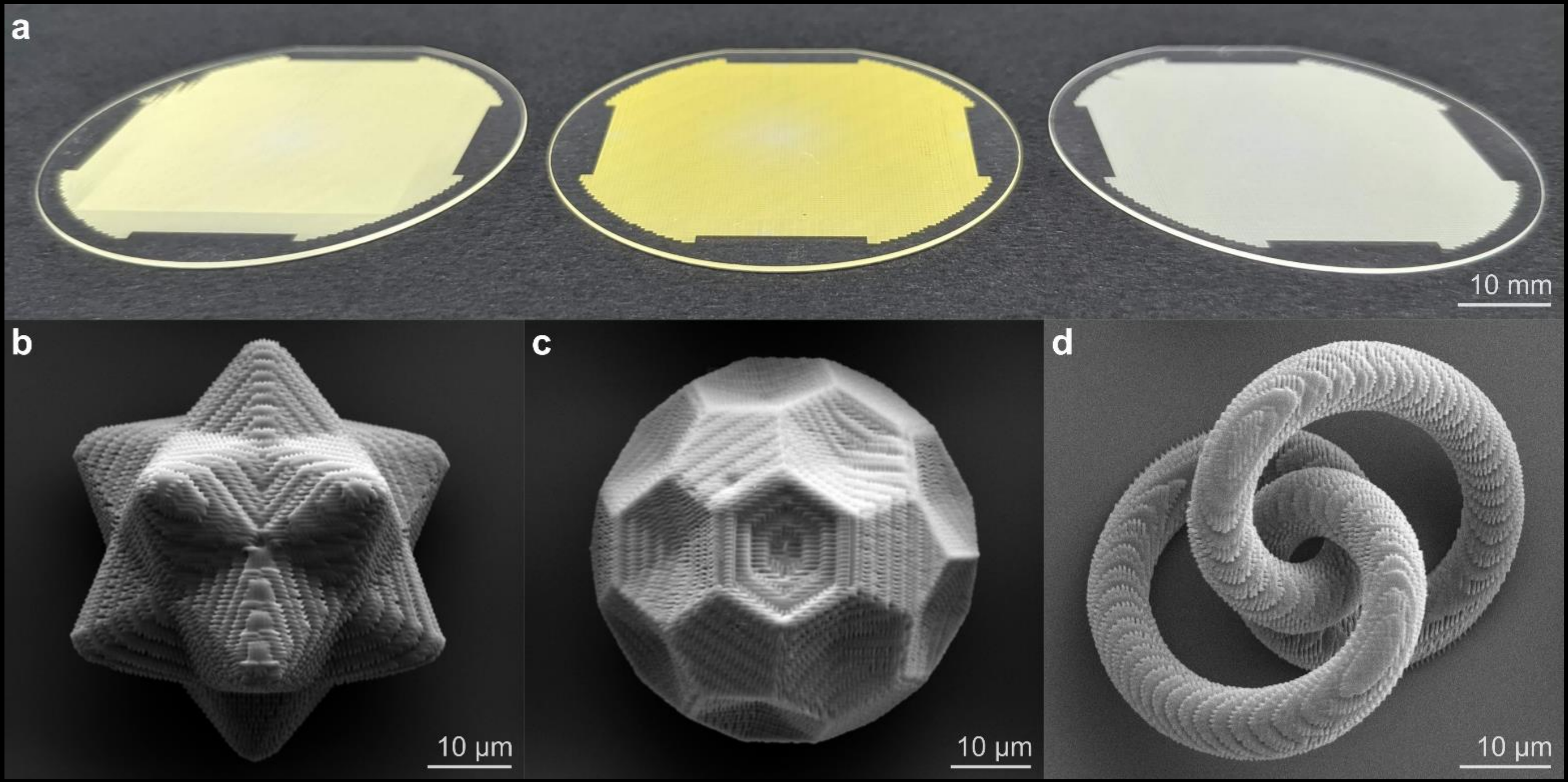
Example I

Many Millions of Printed Particles



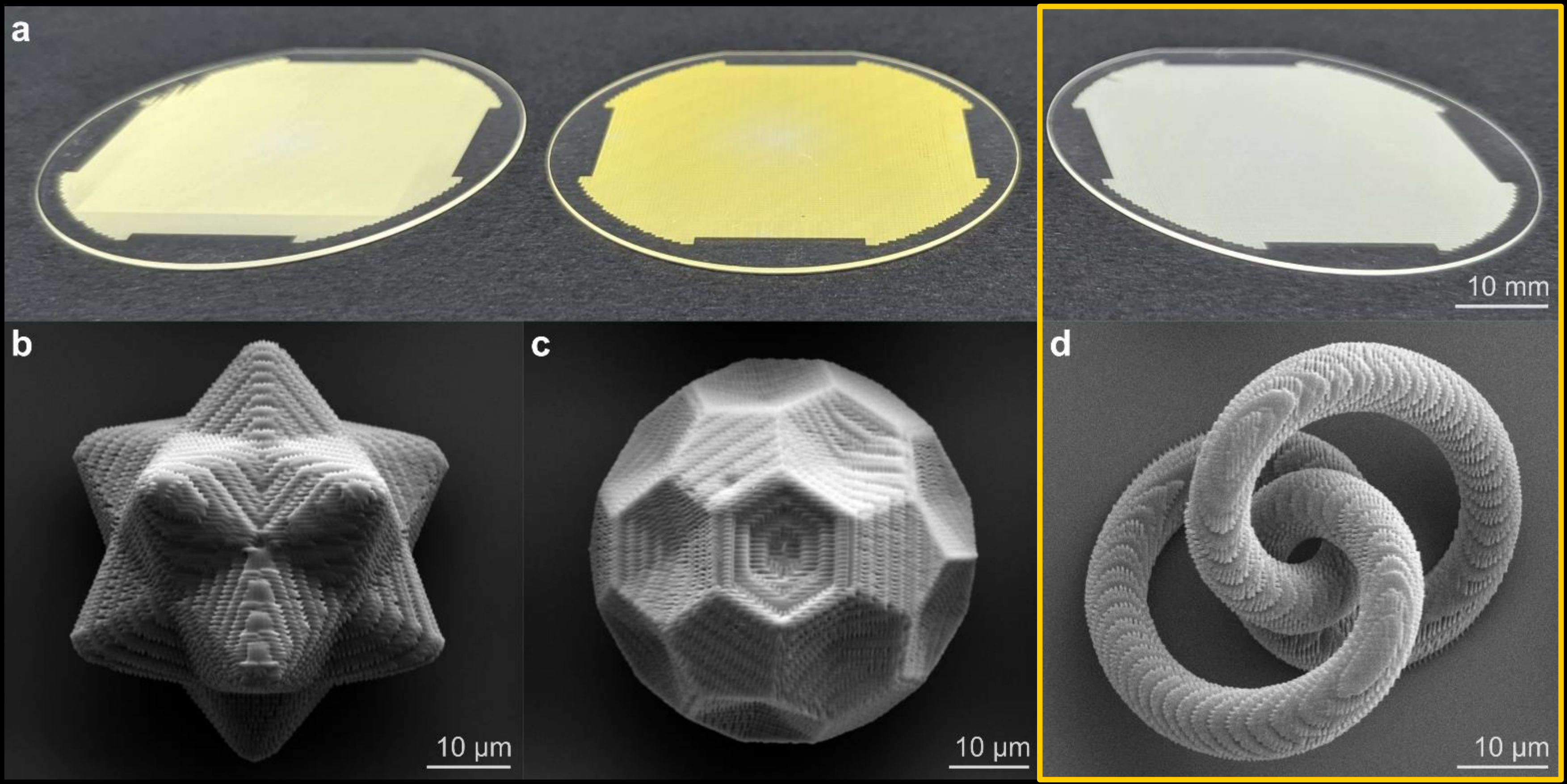
collaboration with pharmacy group of Prof. Regina Scherließ, Univ. Kiel, Germany

Many Millions of Printed Particles



also see: S. Bock *et al.*, Adv. Drug Deliv. Rev. 186, 114341 (2022)

Many Millions of Printed Particles



P. Kiefer *et al.*, submitted (2023)

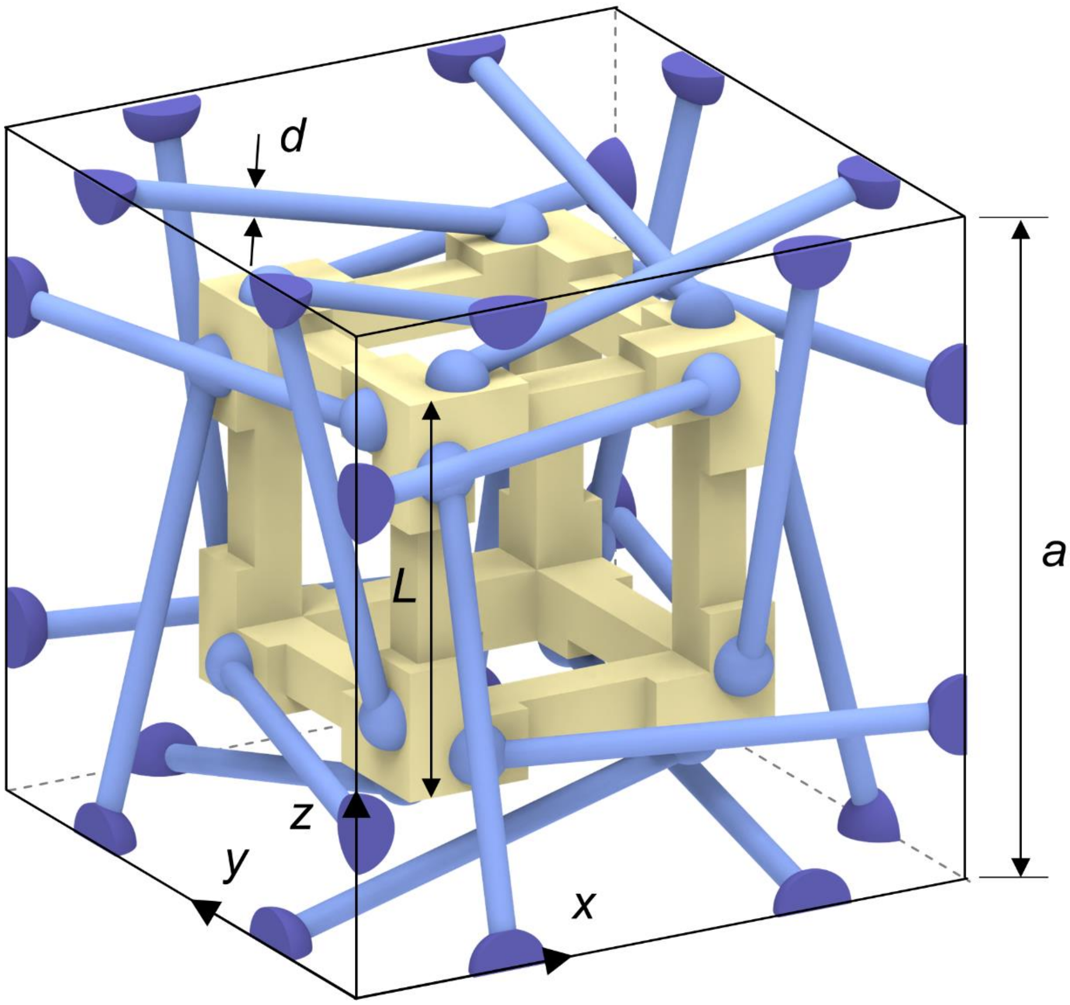
In-Situ Real-Time Movie

# foci:	7×7 = 49
focus speed:	1 m/s
NA:	1.4
magnification:	100×
printing rate:	10^8 voxels/s
wavelength:	790 nm
power @ pupil:	954 mW
photoinitiator:	BBK
monomer:	IP-DIP NPI
wafer:	2 inch diam.

for photoinitiator **BBK**, see: P. Kiefer *et al.*, Adv. Opt. *Mater.* 8, 2000895 (2020)

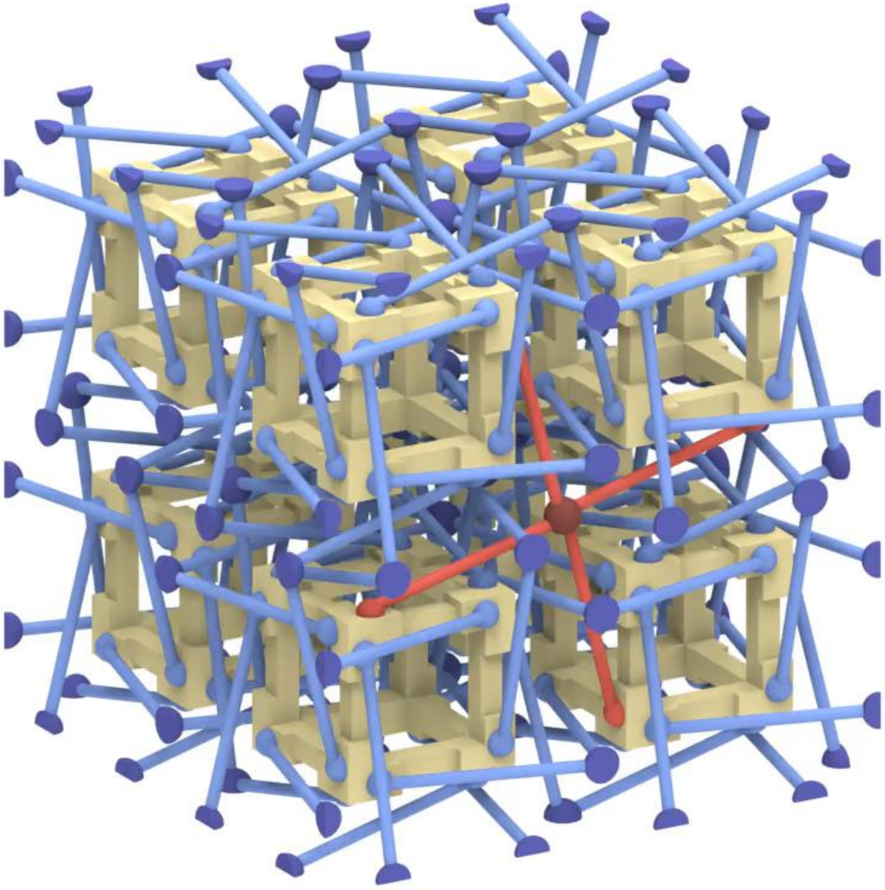
Example II

Chiral Unit Cell



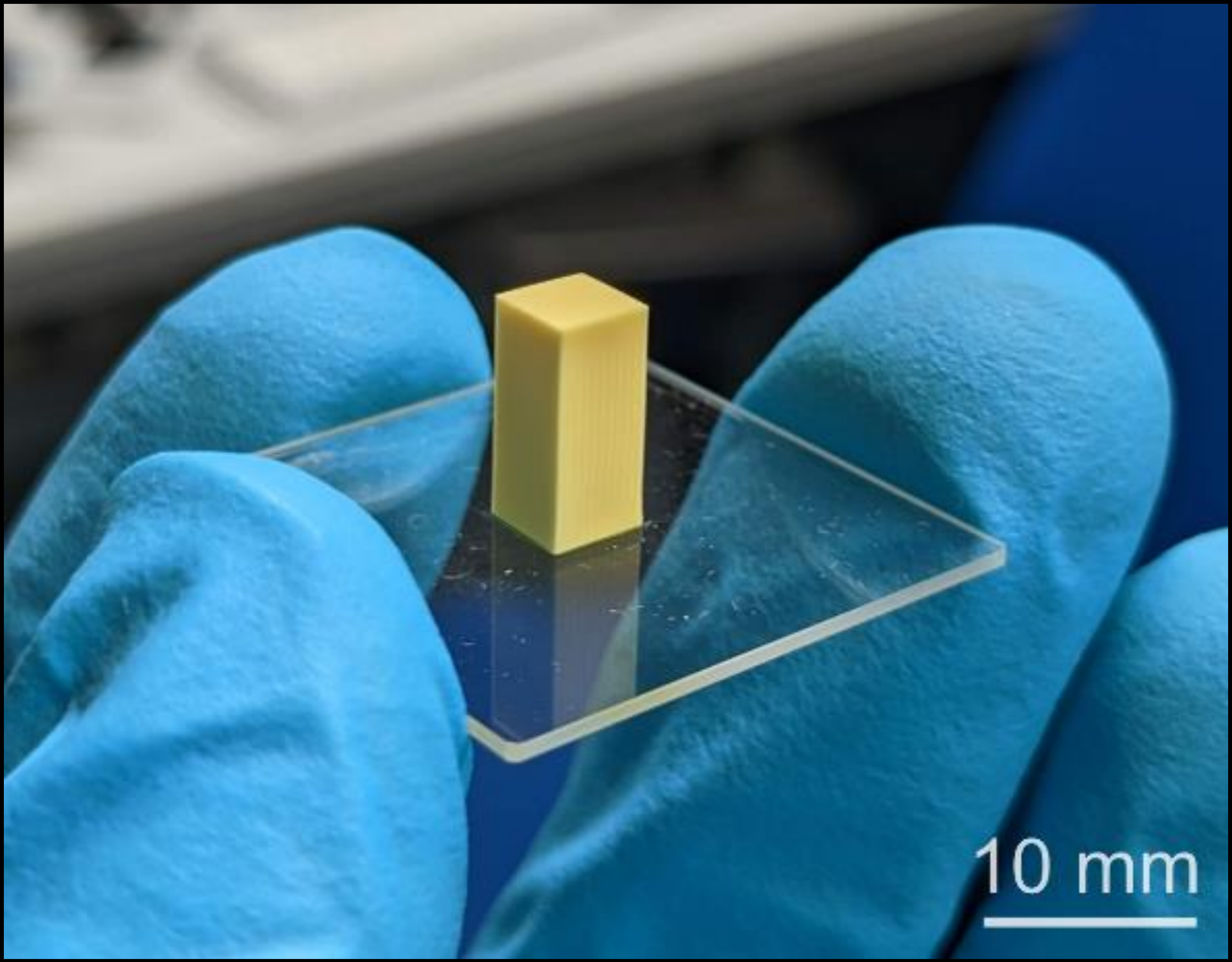
used parameters: $a = 185\,\mu m$, $d/a = 0.04$, $L/a = 0.6$

Cubic Chiral Crystal



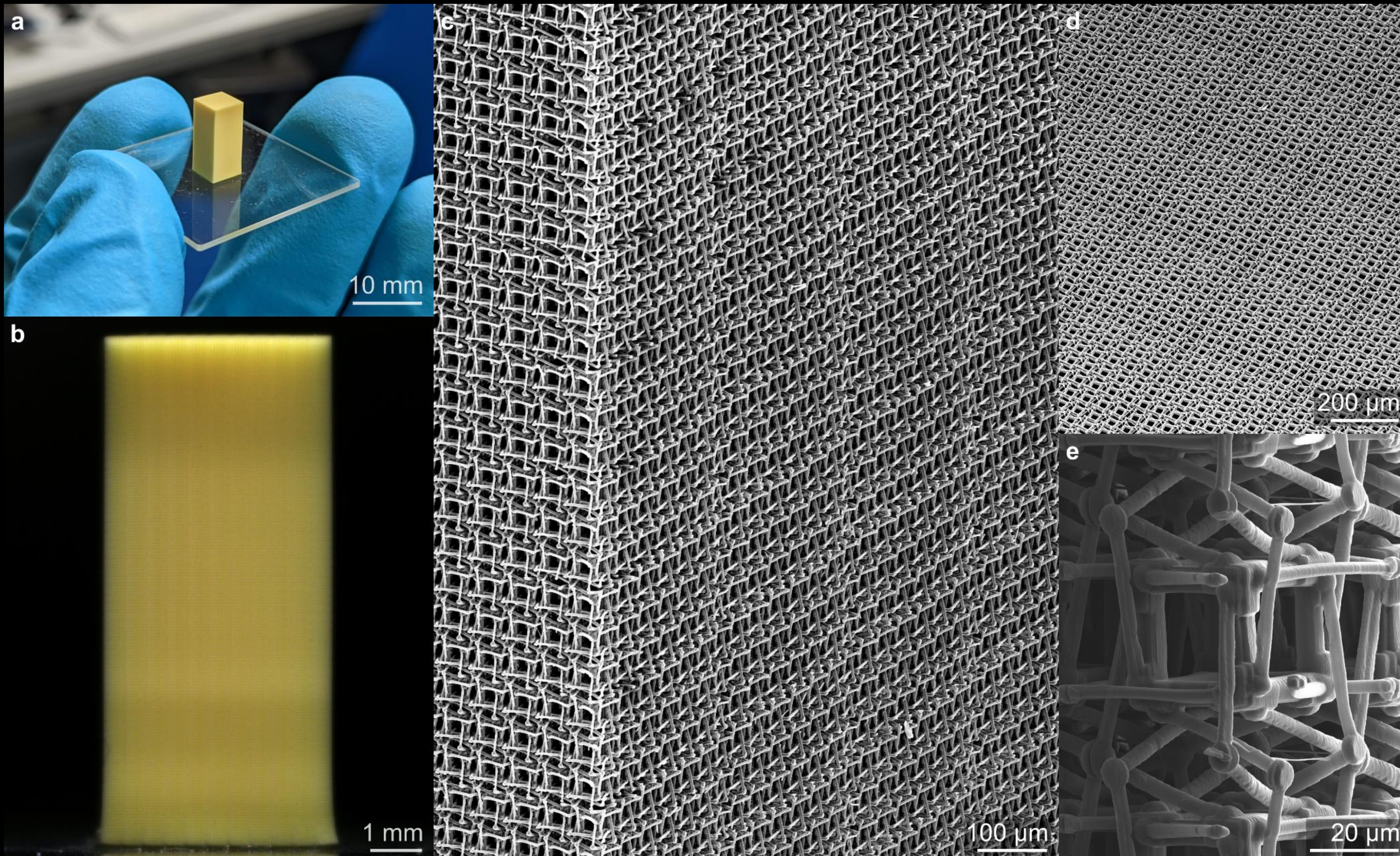
Y. Chen, J.L.G. Schneider, M.F. Groß, *et al.*, Adv. Funct. Mater. 33, 2302699 (2023)

$> 10^{12}$ Voxels; $> 10^{6}$ Unit Cells



$a = 60\,\mu m$, 10^8 voxels/s; P. Kiefer *et al.*, submitted (2023)

> 10^{12} Voxels; > 10^6 Unit Cells



a = 60 µm, 10^8 voxels/s; P. Kiefer *et al.*, submitted (2023)

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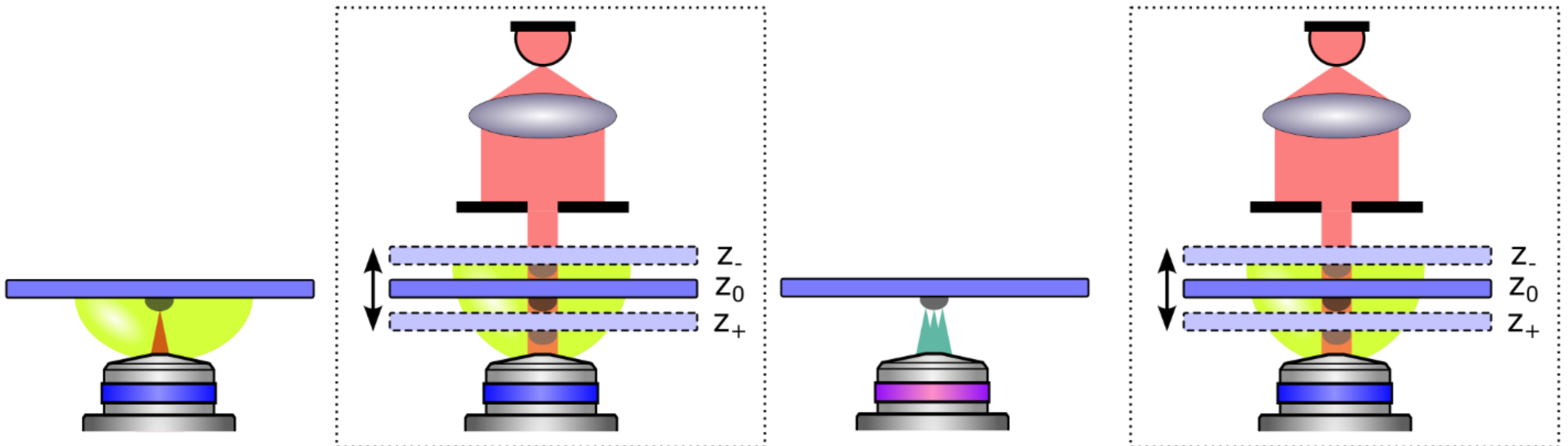
- **Diagnostics of 3D print job during printing, *i.e.*, *in-situ* within the monomer, before development.**
- **Small refractive-index contrast.**
- **Optical inspection must be non-invasive, *i.e.*, must not photo-polymerize monomer.**

R. Zvahelskyi *et al.*, Light: Adv. Manufacturing 3, 39 (2022)

Quantitative Phase Imaging (QPI)



R. Zvagelsky *et al.*, ACS Photon. 10, 2901 (2023)

In Quantitative Phase Imaging (QPI), one needs to solve the transport-of-intensity equation (TIE) for the in-situ accumulated phase difference

$$-\frac{k}{I_0(\vec{r})}\frac{\partial I(\vec{r})}{\partial z} = \vec{\nabla}^2\left(\Delta\varphi_{\mathrm{in-situ}}(\vec{r})\right)$$

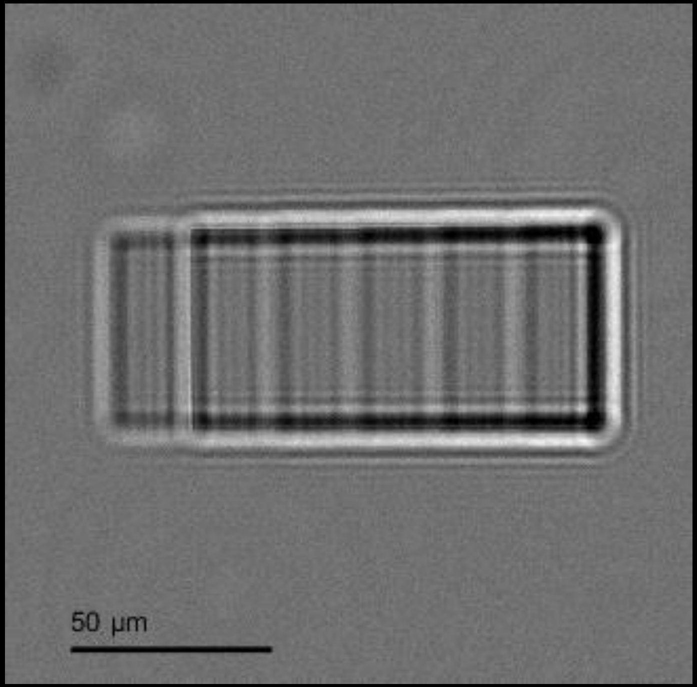
with the optical wavenumber in the immersing resist

$$k = \frac{2\pi\, n_{\mathrm{imm}}}{\lambda_0}$$

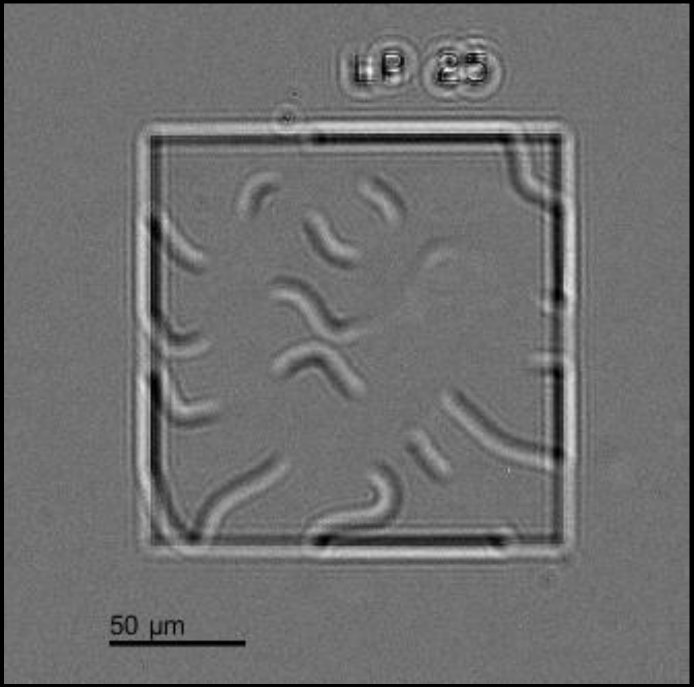
R. Zvagelsky *et al.*, ACS Photon. 10, 2901 (2023)

Wide-Field *z*-Stacks

Example I: Staircase

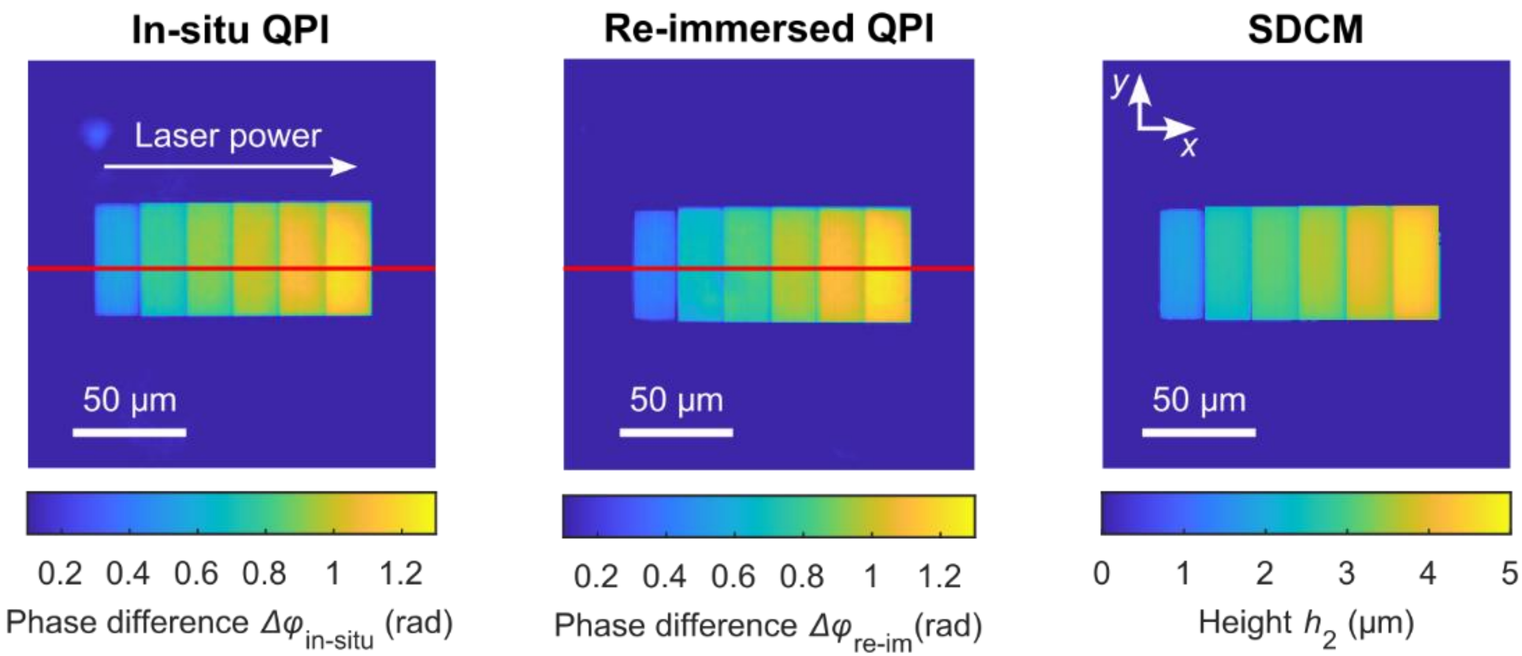


Example II: DOE



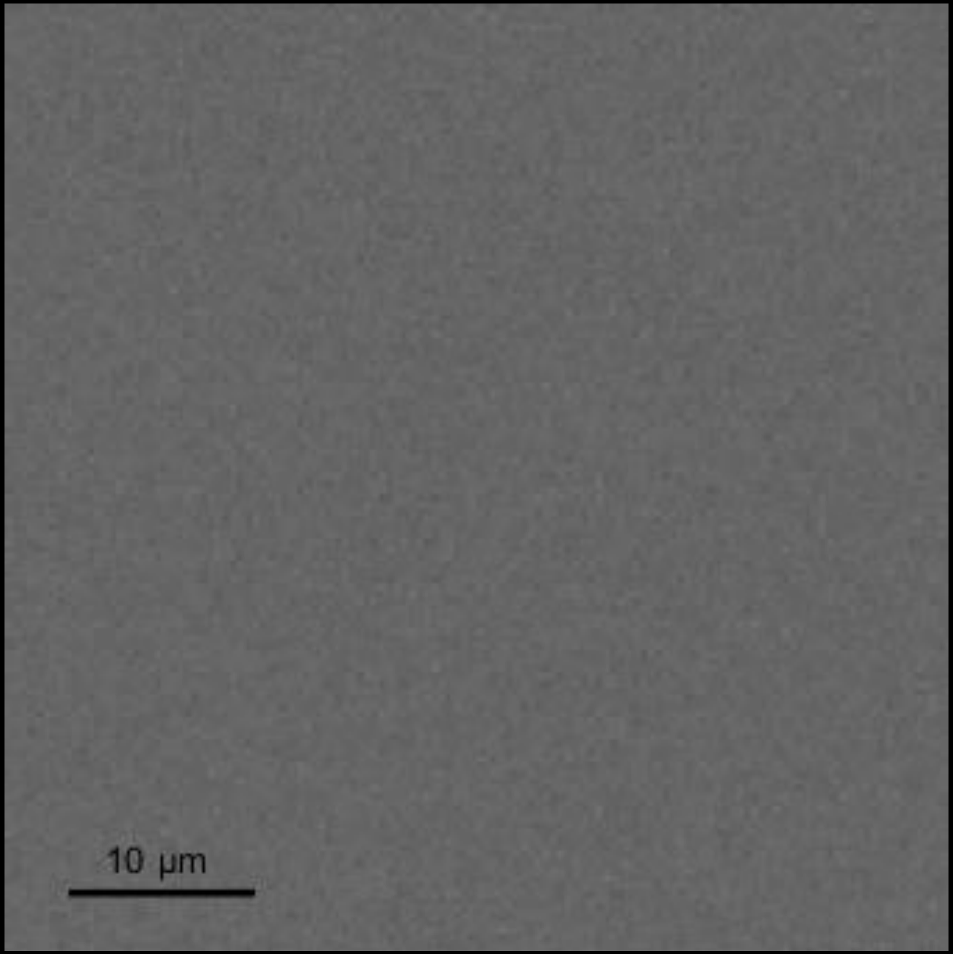
61 defocus images taken **after** completion of the print job; correction applied

Quantitative Phase Imaging (QPI)



R. Zvagelsky *et al.*, ACS Photon. 10, 2901 (2023)

Reconstruction of 3D Structure?



ordinary wide-field images taken **during** print job

2.5D → 3D

ill-defined inverse problem, can be solved by deep learning, trained by computations

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Acknowledgements

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Prof. Stefanie Dehnen (Chemistry, KIT, Germany)
Prof. Carsten Rockstuhl (Physics, KIT Germany)
Prof. Regina Scherließ (Pharmacy, Univ. Kiel, Germany)
Prof. Wolfgang Wenzel (Physics, KIT, Germany)

martin.wegener@kit.edu

martin.wegener@kit.edu